A DIGITAL SIGNAL PROCESSOR FOR DOPPLER RADAR SENSING OF VITAL SIGNS

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Abstract – **A digital signal processor for Doppler radar sensing of vital signs is described. A voltage waveform signal containing respiration and heartbeat signatures is low-pass filtered (0.7 Hz) for the respiration and band-pass filtered (1.0 – 3.0 Hz) for the heart signal. The autocorrelation function is used to calculate the rate per minute for each of these signals. To make the processor more robust, several signal processing techniques are applied. One of these techniques, a method commonly used on audio signals for formant removal, is called center clipping. Another technique is the use of a Hanning window. To reverse the distinct shape left by the Hanning window an "undo" window is applied. The processor is programmed in LabVIEW.**

Keywords – **DSP, Doppler, heart rate, respiration rate, autocorrelation, center clipping, Hanning window.**

I. INTRODUCTION

The treatment of thorax-related illnesses is becoming an increasing problem worldwide. An estimated one hundred million Americans suffer from chronic health conditions including heart disease, lung disorders and diabetes, and treatment for these conditions accounts for three-fourths of total US healthcare costs [1]. Consequently, there is a growing market for appliances that allow both remote monitoring of health parameters and transfer of the recorded data to a physician, for convenience and cost reduction. Non-invasive sensing of circulatory and respiratory movements with a microwave Doppler radar [2] can be used for such remote monitoring. By applying telecommunication devices and frequencies for this remote sensing, the existing telecommunication network can eventually be used to facilitate the transfer of patient data to health care professionals [3].

Microwave Doppler radar monitoring of respiratory [4], cardiac [5] and arterial [6] movements was demonstrated with commercially available waveguide X-band Doppler transceivers in the late 1970's. In the late 1980's a portable microprocessor-based non-invasive cardiopulmonary heart rate monitor was demonstrated [7]. Although it employed simple digital algorithms to determine the heart and respiration rates, the heart rate monitor relied on analogue filters to separate the heart and breathing signals. A bank of batteries provided the power for the entire system, making portability difficult.

Because of the recent rapid expansion of wireless communications and information technology, smaller, lighter, and less expensive circuitry is readily available today. Similar advances in the field of digital signal processing (DSP) open up countless new possibilities. The speed doubling of chips every 18 months (Gordon Moore's "law") is allowing more complex calculations to be performed in ever shorter amounts of time. Bulky analog filters can now be replaced by software implemented algorithms. These technological advances make the construction of a mobile remote monitoring station very feasible. Systems employing digital signal processing already exist [8], but these systems rely on contact measurements. While such non-invasive measurement systems do not compromise the physiological integrity of the subject, in some situations the use of contact sensors may still be disruptive or otherwise unsuitable [2]. A less disruptive non-contact system can be realized by combining a small microwave radio for Doppler radar sensing [9] with the corresponding digital signal processing software. A consequence of this system, however, is that the received signals are corrupted with much more noise than those obtained with contact measurements. Therefore, a robust digital signal processor is necessary to correctly extract useful data.

In this paper, a digital signal processor for Doppler radar sensing of vital signs, implemented in LabVIEW [10], is described. Several implemented techniques are described which make the processing more robust. Respiration and heart rates are successfully extracted from signals received from distances of up to two meters from the subject.

II. METHODOLOGY

According to Doppler theory, a constant frequency signal reflected off an object with a periodically varying displacement will result in a reflected signal at the same frequency, but with a time varying phase, $\phi(t)$. The reflected signal is effectively phase modulated (PM). If the change in displacement is small compared to the wavelength of the signal, the phase change will be small, and the PM signal can be directly demodulated by mixing it with a portion of the original signal [9]:

$$sin(\omega t+\phi(t)) \cdot cos(\omega t) = sin(\phi(t)) + high\ frequency\ terms \quad (1)$$

where $cos(\omega t)$ is the original signal with constant frequency ω, and $sin(\omega t+\phi(t))$ the reflected signal with phase shift. The right hand side of (1) can then be filtered for the phase shift term $sin(\phi(t))$ [3]. The phase can be extracted from this term by using a small signal approximation: $sin(\phi(t)) \approx \phi(t)$ for small $\phi(t)$.

Report Documentation Page

Report Date	Report Type	Dates Covered (from... to)
25 Oct 2001	N/A	-

Title and Subtitle	Contract Number
A Digital Signal Processor for Doppler Radar Sensing of Vital Signs	
	Grant Number
	Program Element Number

Author(s)	Project Number
	Task Number
	Work Unit Number

Performing Organization Name(s) and Address(es)	Performing Organization Report Number
ICT Group Department of Electrical Engineering Delft University of Technology Delft, The Netherlands	

Sponsoring/Monitoring Agency Name(s) and Address(es)	Sponsor/Monitor's Acronym(s)
US Army Research, Development & Standardization Group (UK) PSC 802 Box 15 FPO AE 09499-1500	
	Sponsor/Monitor's Report Number(s)

Distribution/Availability Statement
Approved for public release, distribution unlimited

Supplementary Notes
Papers from 23rd Annual International Conference of the IEEE Engineering in Medicine and Biology Society, October 25-28, 2001, held in Istanbul, Turkey. See also ADM001351 for entire conference on cd-rom.

Abstract

Subject Terms

Report Classification	Classification of this page
unclassified	unclassified

Classification of Abstract	Limitation of Abstract
unclassified	UU

Number of Pages
4

Analogous to the phase shift on a transmission line terminated with a load at a varying position, this time varying phase is proportional to the displacement, $x(t)$:

$$\phi(t) = \frac{4\pi}{\lambda} x(t) \qquad (2)$$

where λ is the wavelength of the signal. The demodulated signal is thus proportional to the periodic displacement of the reflecting object, as in (2). If the change in displacement is small compared to the wavelength, the demodulated signal is proportional to the periodic displacement of the reflecting object. If this object is a person's chest, the demodulated voltage waveform represents displacement due to respiration and heart activity.

A block diagram of the signal processor is displayed in Fig. 1. The incoming demodulated voltage waveform was filtered in such a way as to separate the two components. The subject's normal (resting) respiration lay somewhere in the order of 20 breaths per minute. The chosen range for the respiration was between 0 and 40 breaths per minute. A 4th order low-pass Butterworth filter with cut-off frequency at 0.7 Hz selected signals in the mentioned range. The resting heart rate of the subject varied anywhere between 60 and 120 beats per minute. A 4th order band-pass Butterworth filter with cut-off frequencies at 1 and 3 Hz selected an adequate range of 60 – 180 beats per minute.

A sliding window was then passed over the waveform. All calculations were performed on the data inside the window. A typical window size was 10 seconds: this interval provided enough data for reliable calculation, but could still track rapid changes in heart or respiration rate. The sliding window was shifted over the waveform in one sample increments. Up to 50 samples per second could still be handled in real-time in a 10 second window. After windowing some enhancements techniques were applied to improve the quality of the two separated signals. One technique was using a Hanning window, which prevented spectral leakage and improved the analysis of acquired signals. Unfortunately, it also left a distinct shape on the autocorrelation function response. This was remedied, however, by multiplying the result of the autocorrelation by the inverse of the Hanning window (a so called "undo" window).

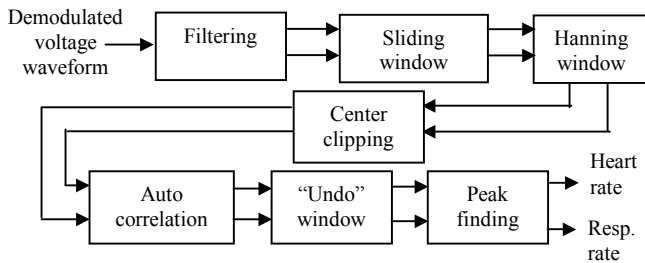Another enhancement technique used was a center clipper [11]. This function, commonly used in the processing of audio data, was used to remove unwanted peaks in the signal. The center clipper function was defined as follows:

$$
\begin{aligned}
c(n) &= 0 && \text{if } |s(n)| \le k \cdot a_{max} \\
&= s(n) && \text{if } |s(n)| > k \cdot a_{max} \qquad (3)
\end{aligned}
$$

where $c(n)$ was the output signal, $s(n)$ the input signal, and a_{max} was the maximum amplitude of the signal in the specified window. The user could set the factor k, and it determined the threshold at which the signal was cut off. An illustration of the process of center clipping is shown in Fig. 2.

After these enhancements, the actual determination of the respiration and heart rate starts. A commonly used method to determine the period of a signal is the autocorrelation function [8]. One of the properties of the autocorrelation function is that if the input signal contains a periodic component, the autocorrelation function will contain a periodic component with the same frequency.

The resulting output signal after autocorrelation contained peaks at integer intervals of the period of the signal. The peak finding used an algorithm that fitted a quadratic polynomial to a sequential group of three samples. This group was moved in one sample increments inside the window. The slope of the second derivative of the fit was checked to determine if a peak or valley occurred. Using these peaks, the period of a given signal could be determined. The average period, taken over the first three peaks on either side of the 0-lag peak, was used. It was then straightforward to determine the rate per minute of the given signals.

The test signals used as input were taken in an anechoic chamber, using a directional antenna facing a test subject seated at a distance varying between 1 and 2 meters [9]. The received signal was passed through a 12 dB/octave roll-off band-pass filter (Stanford Research Systems SR560) with 0.03 – 10 Hz bandwidth. This was done as a simple means to eliminate DC offset, avoid aliasing and minimize out of band noise. As a result, the resolution of vital sign fluctuations in each sample was optimized.
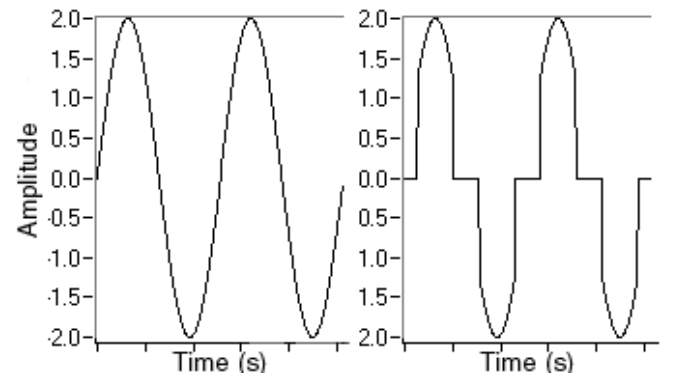

Fig. 2. Illustration of the process of center clipping. K=0.6, which gives a threshold of 1.2.

Fig.1. Block diagram of *TeleSensor*.

	Success ratio[a] of heart rate recovery [%]
Dataset 1	93.84
Dataset 2	88.93
Dataset 3	92.53

[a] Success ratio is the percentage of time the calculated rate is within 2% of the reference rate.

Analog to digital conversion was done with a HP Infinium digital oscilloscope (HP 54815A), with a sampling rate varying between 25 and 50 samples per second.

For these test signals, the success ratio was calculated. This ratio was defined as the percentage of time the calculated rate was within 2% of the reference rate. The success ratio was not calculated for the first three seconds, since this interval did not contain enough information to calculate the heart rate. Since there was no reference available for a breathing signal, it was not possible to calculate its success ratio.

III. RESULTS

Some representative results of the digital signal processor have been displayed in Table I. Dataset 1 was a 20 second sample taken with a 2.4 GHz carrier wave from an antenna placed at 1 meter from the subject. Dataset 2 was a 20 second sample using an 850 MHz carrier wave from a distance of 1 meter. The last set, dataset 3 utilized a 2.4 GHz wave to obtain a 25 second sample also from a distance of 1 meter. The first two sets had a sample rate of 50 samples per second. The last set had a sample rate of 25 samples per second. The window size used on each of the datasets was 10 seconds. The center clipper factor was set to 0.2, which was slightly lower than the value typically used in audio applications (0.3).
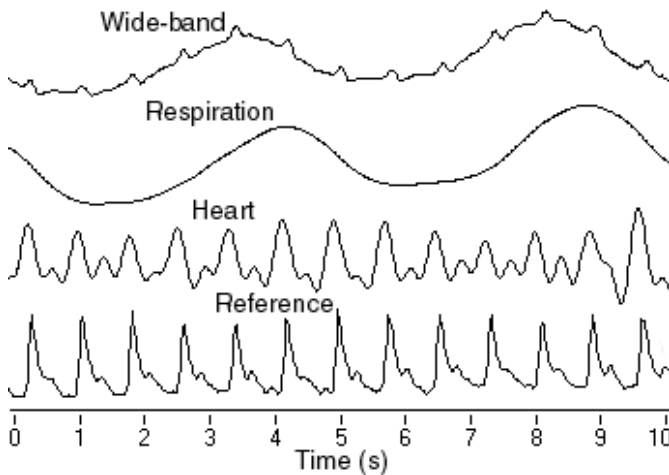

Fig. 3. Wide-band (at 1 meter distance), respiration (0.00 - 0.70 Hz), heart (1.00 – 3.00 Hz) and pressure pulse reference signals.
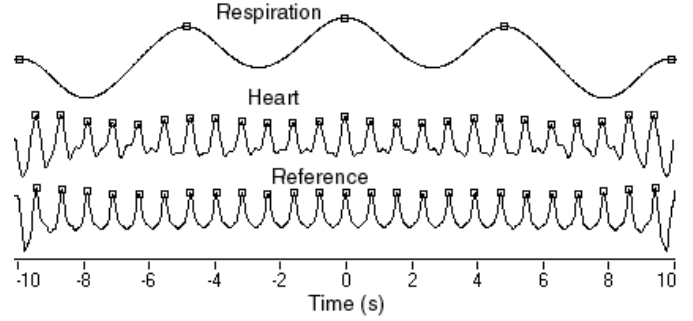

Fig. 4. Autocorrelated signals corresponding to the respiration, heart and reference signals shown in Fig. 3.

IV. DISCUSSION

Part of a given dataset, taken with an antenna frequency of 2.4 GHz at a distance of 1 meter for a duration of 20 seconds, is shown in Fig. 3. It can be seen that the respiration (second trace) and heart signature (third trace) can be recovered from the original raw (wide-band) signal (top trace). A finger pressure pulse sensor (UFI-1010 pulse transducer) is used during the measurements to provide a reference signal for heart activity (bottom trace). In Fig. 4 the calculated autocorrelation function is shown. From the peaks, marked with small squares, the respiration and heart rate are calculated to be 17 breaths per minute and 77 beats per minute, respectively. The calculated heart rate corresponds quite well to the reference heart rate, which is also 77 beats per minute.

The calculated history plot of dataset 2 is shown in Fig. 5. The calculated heart rate, after an initial settling time of 3 seconds, tracks the reference rate within a couple of beats (Fig 5(a)). The breathing takes a bit longer to settle, about 5 seconds (Fig. 5(b)). This is due to the larger period of the breathing signal.

The use of the center clipper, as illustrated in Fig. 6, eliminates peaks that are not associated with the fundamental of the heartbeat. A closer analysis of the
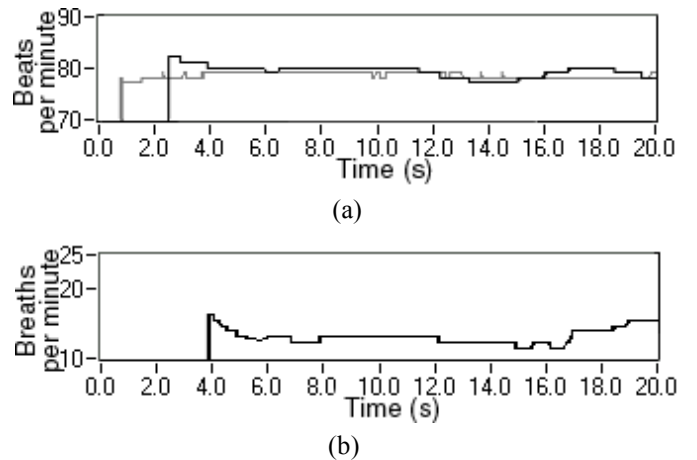

(a)

(b)

Fig. 5. History windows showing the calculated (black) and reference (gray) heart rate (a) and the calculated respiration rate (b).
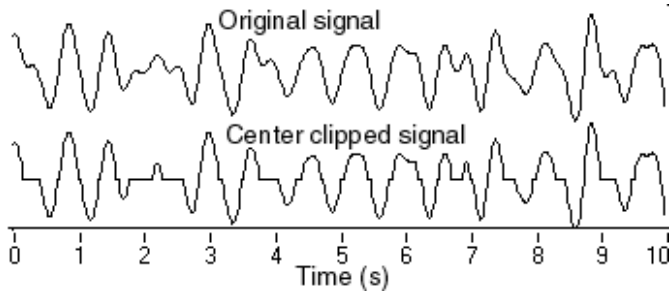
Fig. 6. Center clipped heart rate signal, showing the clipping of the secondary beat.

cardiac pulse, shown as "heart" in Fig. 3 shows a small spike halfway each heartbeat. This is known as the dicrotic notch, which signifies a sudden drop in pressure after systolic contraction. It is caused by a small reflux flow of blood back into the aortic valve and coronary vessels. This dicrotic notch in the heart signal is clipped. This can be seen clearly in Fig. 6 at time intervals 2 and 9 seconds.

There are several reasons why the signal processing is done digitally. Before any information can be extracted from the demodulated voltage waveform, the heart and respiration signals need to be separated. This can be done by using hardware ([7], [9]), such as analog filters and amplifiers, or by using digital signal processing software. Digital processing offers implementation flexibility, filters with closer tolerances, utilizes fewer components and has an overall lower price. DSP software not only replaces hardware filters for separation of heart and breathing signals, but also provides convenient means of extracting heart and breathing rates. For these reasons a digital signal processor called *TeleSensor* is developed.

IV. CONCLUSION

A signal processor for the determination of respiration and heart rates in Doppler radar measurements is described. The processor can reliably calculate both rates for a subject at distances as large as two meters. The rate determination is based on autocorrelation and uses several enhancement techniques, including a center clipper. Several representative results are included to show the future potential of using the processor for this purpose. Calculated heart rates agree for over 88% of the time with the reference rate, within a 2% margin, for all datasets. These results indicate excellent prospects for remote monitoring of vital signs through non-contact radar techniques.

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